

Project Description Form

Core 20XX Call

Project Acronym	
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Host Institution	

1 Introduction: Originality of the Research Project

The field of spacecraft design is a multifaceted endeavor, encompassing a wide array of scientific and engineering disciplines. The proposed research project, "Autonomous AI Agents for Spacecraft Operations," aims to revolutionize space mission design by introducing innovative approaches that enhance utility for stakeholders. This is achieved by optimizing mission design beyond the constraints of traditional, conservative methodologies. The originality of this research is underscored by its focus on three key aspects of mission design:

- Thorough and efficient exploration of alternative mission concepts.
- Addressing multi-objective design problems, which often involve complex trade-offs between conflicting objectives.
- Leveraging AI technologies to enhance decision-making processes and system integration.

1.1 Exploration of Alternative Concepts

The research emphasizes the importance of exploring alternative mission concepts more thoroughly and efficiently. This approach allows for the identification of innovative solutions that can provide higher utility and adaptability in dynamic space environments. By moving away from the stagnancy of conservative mission design, the project seeks to unlock new opportunities for mission optimization.

1.2 Multi-Objective Design Problems

Space mission design inherently involves multi-objective problems, where the goal is to find a balance between various conflicting objectives, such as fuel consumption and travel time. In this context, the concept of a single global optimum is replaced by the Pareto front, which represents a set of non-dominated solutions. These solutions express the trade-offs between different objectives, guiding engineers towards the best possible outcomes.

1.3 AI-Driven Innovations

The integration of AI technologies into spacecraft operations is a cornerstone of this research. AI offers the potential to enhance data analysis, enable autonomous systems, and improve navigation efficiency. However, the transferability of AI solutions across different tasks remains a challenge, often due to a lack of understanding of their strengths and weaknesses. This project aims to address these challenges by developing AI agents capable of robust decision-making under uncertainty and seamless integration with existing systems.

1.3.1 Challenges and Opportunities

The project acknowledges the challenges associated with AI integration in space exploration, such as limited real-time communication and the complexity of space data. By addressing these challenges, the research aims to reduce human involvement in mission-critical tasks, thereby minimizing human error and enhancing mission efficiency and safety. The potential impacts on the space exploration industry include increased mission efficiency, reduced operational costs, and enhanced safety and reliability of space missions.

In summary, the originality of this research project lies in its innovative approach to spacecraft design, its focus

on multi-objective optimization, and its pioneering use of AI technologies to enhance mission autonomy and efficiency. Through these efforts, the project seeks to contribute significantly to the advancement of space exploration.

2 Hypothesis, Research Objectives and Envisaged Methodology

The development of autonomous AI agents for spacecraft operations presents a transformative opportunity in the field of space exploration. This section outlines the hypothesis, research objectives, and the envisaged methodology that will guide the project towards achieving its goals.

2.1 Hypothesis

The central hypothesis of this research is that integrating autonomous AI agents into spacecraft operations, specifically in Guidance, Navigation, and Control (GNC) and Attitude and Orbit Control Systems (AOCS), will significantly enhance mission efficiency and safety. This enhancement is expected to be achieved by reducing human involvement in mission-critical tasks, thereby minimizing human error and improving decision-making under uncertainty.

2.2 Research Objectives

The research objectives are structured to systematically address the hypothesis and are as follows:

1. **Development of High-Integrity GNC Algorithms:** To create robust algorithms capable of handling the complexities of spacecraft navigation and control autonomously.
2. **Intelligent Docking and Capture Techniques:** To innovate methods for autonomous docking and capture, ensuring precision and reliability in spacecraft operations.
3. **Autonomous Mission Planning:** To design AI systems that can independently plan and execute mission tasks, adapting to dynamic space environments.
4. **Multi-Agent Coordination:** To enable seamless coordination among multiple AI agents, ensuring efficient task distribution and execution.
5. **Benchmark Analysis:** To conduct a comprehensive evaluation of the AI-based GNC pipeline, including Image Generation, Image Processing, Navigation, and Guidance Control.

2.3 Envisaged Methodology

The methodology for this research is designed to rigorously test the hypothesis and achieve the outlined objectives. It involves several key components:

2.3.1 Modeling and Simulation

Models of the spacecraft, its environment, and the on-board autonomy will be developed to perform inference and validate the AI systems. These models will simulate various operational scenarios to test the AI agents' performance under different conditions.

2.3.2 Data Processing and Analysis

Data from spectrometers, cameras, and environmental sensors will be processed using advanced techniques such as filtering, normalization, and interpolation. This preprocessing is crucial for correcting noise and calibrating measurements, thereby improving the quality of the signal for further analysis.

2.3.3 Experimental Validation

Experiments will be conducted to validate the proposed methodologies and technological achievements. The TANGO satellite from the Swedish PRISMA mission will serve as a case study, providing a real-world context to demonstrate the AI agents' capabilities.

2.3.4 Evaluation and Benchmarking

A comprehensive benchmark analysis will be performed to evaluate the AI-based GNC pipeline. This analysis will assess the system's ability to manage autonomous relative dynamics robustly, ensuring that the AI agents meet the required performance standards.

2.3.5 Stakeholder Engagement

Stakeholders will be actively involved in addressing technical, ethical, and legal challenges. Their input will be crucial in ensuring the explainability, transparency, and legal compliance of the AI systems.

By following this structured methodology, the project aims to achieve significant advancements in the autonomy and efficiency of spacecraft operations, ultimately contributing to the broader goals of space exploration.

3 Expected Outcomes / Impact

The integration of autonomous AI agents in spacecraft operations is anticipated to yield significant advancements in the efficiency and safety of space missions. This section outlines the expected outcomes and impacts of the project, focusing on the technical, operational, and strategic benefits.

3.1 Technical Outcomes

The project aims to achieve several technical innovations, including:

- **Improved AI Reliability:** By developing robust AI algorithms capable of operating under uncertainty, the project seeks to enhance the reliability of AI systems in space environments.
- **Advanced Decision-Making:** The AI agents will be equipped with sophisticated decision-making capabilities, allowing them to autonomously manage complex spacecraft functions.
- **Seamless System Integration:** Ensuring compatibility with existing spacecraft systems is crucial. The project will focus on integrating AI agents without disrupting current operations.

3.2 Operational Impact

The deployment of AI agents is expected to transform spacecraft operations by:

- **Reducing Human Involvement:** By automating mission-critical tasks, the project aims to minimize human intervention, thereby reducing the potential for human error.

- **Enhancing Mission Efficiency:** Autonomous AI agents can optimize resource allocation and mission planning, leading to more efficient space missions.
- **Increasing Safety:** The ability of AI agents to operate independently in dynamic environments is expected to enhance the overall safety of space missions.

3.3 Strategic Impact

The strategic implications of integrating AI in spacecraft operations include:

- **Cost Reduction:** By improving operational efficiency and reducing the need for extensive human oversight, the project is expected to lower the costs associated with space missions.
- **Industry Advancement:** The successful implementation of AI agents could set a precedent for future space missions, encouraging further innovation and investment in AI technologies.
- **Enhanced Data Utilization:** AI-driven data analysis will enable more effective use of data collected from space missions, facilitating scientific discoveries and insights.

3.4 Outcome Prediction and Evaluation

To ensure the successful realization of these outcomes, the project employs a rigorous outcome prediction and evaluation process. This involves:

- **Low Fidelity to High Fidelity Simulations:** Initial low fidelity evaluations provide a preliminary understanding of potential outcomes, which are then refined through high fidelity simulations using a Monte Carlo approach across 10,000 scenarios.
- **Outcome Aggregation and Analysis:** The aggregated results from simulations are analyzed to predict the impact of AI agents on mission progress and performance, as illustrated in Figure ??.

In conclusion, the Autonomous AI Agents for Spacecraft Operations project is poised to make significant contributions to the field of space exploration, with expected outcomes that promise to enhance mission efficiency, safety, and cost-effectiveness. The project's success will depend on overcoming challenges related to AI reliability and integration, ultimately paving the way for more autonomous and intelligent space missions.

4 Explanations on the Management of Ethical Issues and Data Protection

The integration of autonomous AI agents in spacecraft operations presents significant ethical and data protection challenges. As AI systems become more prevalent in space missions, it is crucial to address these issues to ensure the responsible and secure use of AI technologies. This section outlines the ethical considerations and data protection strategies pertinent to the development and deployment of AI in space systems.

4.1 Ethical Considerations

The use of AI in space systems raises several ethical questions, particularly concerning decision-making, accountability, and transparency. A report by the British House of Commons highlights the importance of transparent decision-making, minimizing bias, and ensuring accountability and privacy in AI systems ?. The European

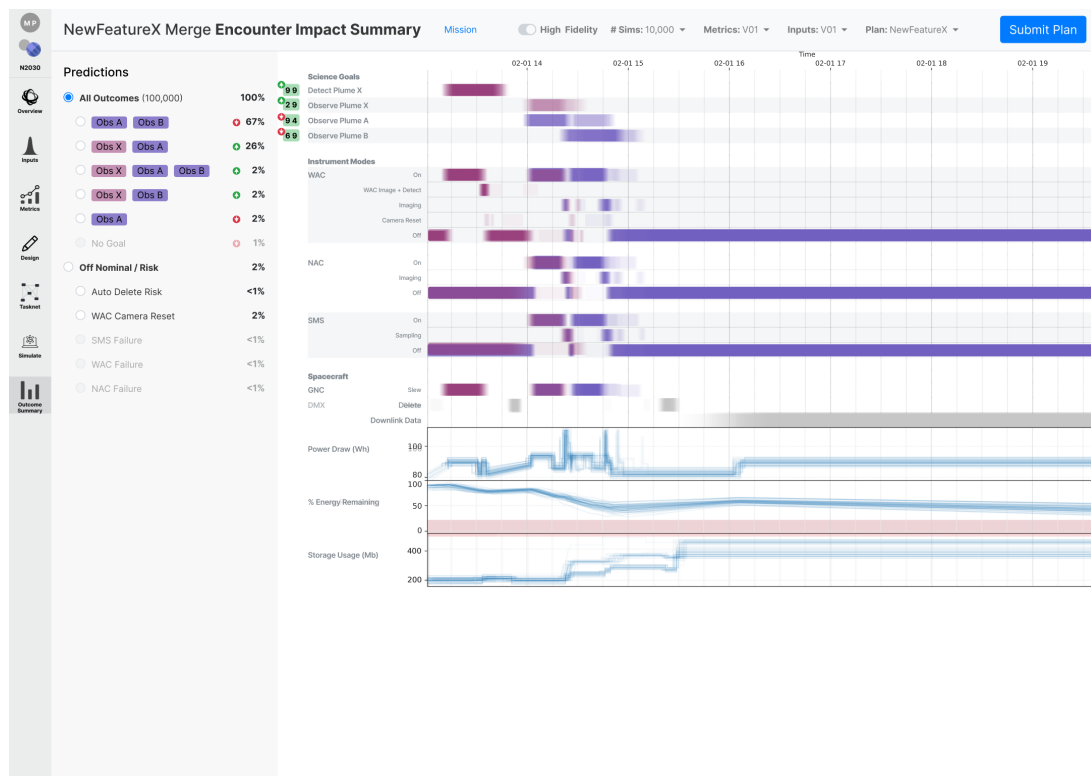


Figure 1: Mission Planning Prediction Results tool: shows the aggregated summary of all simulation runs for a given task network.

Commission's High-Level Expert Group on Artificial Intelligence (AI HLEG) has also published the "Ethics Guidelines for Trustworthy AI," which emphasize the following principles:

- **Ethical Purpose:** AI development, deployment, and use should respect fundamental rights and applicable regulations, ensuring an ethical purpose ?.
- **Technical Robustness:** AI systems must be technically robust and reliable to prevent unintentional harm, even with good intentions ?.

These guidelines serve as a foundation for developing AI systems that are not only effective but also ethically sound.

4.2 Data Protection Strategies

AI systems in space operations rely on vast amounts of data, raising concerns about data security and privacy. Effective data protection strategies are essential to safeguard sensitive information and ensure compliance with legal and ethical standards. Key strategies include:

4.2.1 Access Management

Implementing robust access management protocols is crucial to protect sensitive data. This involves defining user and group access rules to control who can view or modify data. Centralized authentication services, such as Active Directory, can facilitate secure access management ?.

4.2.2 Data Version Control

Maintaining a comprehensive data version control system helps track the original source of data and document changes through commit history with comments. This ensures data integrity and facilitates accountability in data handling processes ?.

4.2.3 Data Standardization

Standardizing data formats, including labeling standards, column naming conventions, and data type and unit standards, is essential for ensuring data consistency and interoperability across different systems ?.

4.3 Legal and Ethical Challenges

The deployment of AI in space systems also presents legal challenges, such as defining accountability and liability in AI-driven decision-making processes. Researchers have emphasized the need for AI ethicists to navigate these challenges and ensure that AI technologies are developed and used responsibly ?.

In conclusion, addressing ethical issues and data protection in AI systems for spacecraft operations is critical for ensuring the safe and responsible use of AI technologies. By adhering to established ethical guidelines and implementing robust data protection strategies, stakeholders can mitigate potential risks and enhance the reliability and trustworthiness of AI systems in space missions.

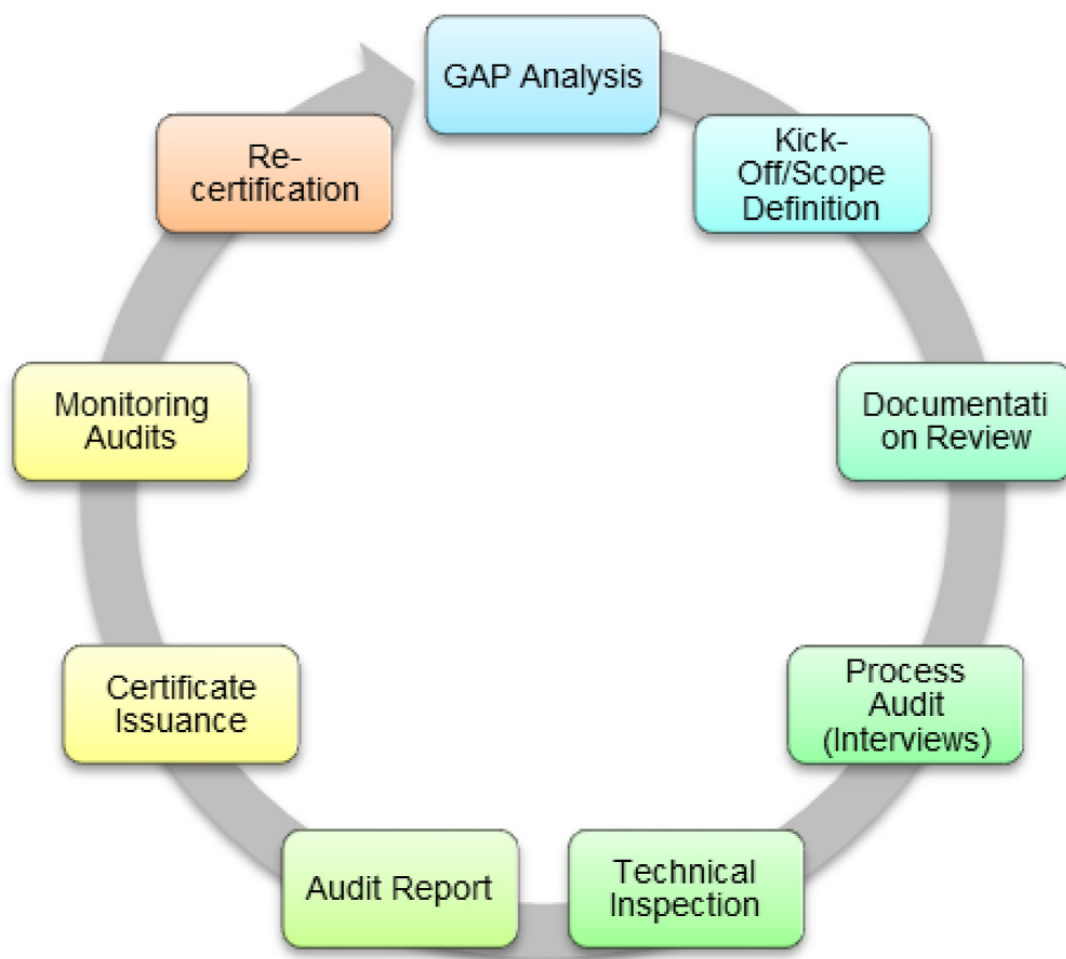


Figure 2: Functional diagram of the Prepare step of the AI/ML workflow.

5 Comment on Resubmission (if applicable)

In the context of the ongoing development of autonomous AI agents for spacecraft operations, the resubmission of our research proposal has been informed by recent advancements and feedback from previous reviews. This section outlines the key updates and enhancements made in the latest revision, version 4, dated July 2023.

5.1 Incorporation of Current AI Technology in Space

The revised proposal integrates insights from the publication titled "Precision Medicine for Long and Safe Permanence of Humans in Space," which highlights the current state of AI technology in space. This includes a detailed comparison of computational density per watt between state-of-the-art radiation-hardened processors and commercial embedded processors, as illustrated in Figure ???. Such comparisons are crucial for understanding the trade-offs in power efficiency and computational capabilities, which directly impact the design and deployment of AI systems in space environments.

Figure 3: Comparison of Computational Density Per Watt of State-of-the-art Rad-Hard Processors and Commercial Embedded Processors.

5.2 Addressing New Scientific Goals and Objectives

The resubmission also addresses the emerging scientific goals that necessitate the coordination of multiple spacecraft for simultaneous observations. This requirement has driven significant research and development efforts in software applications and processes used during space missions. The proposal now includes strategies for enhancing the autonomy of AI agents to manage these complex, multi-agent scenarios without ground intervention, thereby increasing mission efficiency and reducing operational costs.

5.3 Enhancements in AI Reliability and Decision-Making

Recent technological advancements in AI techniques have been incorporated to improve the adaptiveness and reliability of autonomous systems. The proposal now includes a comprehensive framework for evaluating AI-based Guidance, Navigation, and Control (GNC) pipelines, ensuring robust autonomous management of relative dynamics. This framework is supported by a case study using the TANGO satellite from the Swedish PRISMA mission, demonstrating the AI agent's performance under various conditions.

5.4 Feedback and Iterative Improvements

Feedback from stakeholders has been instrumental in refining the proposal. The iterative process involved revisiting mission goals, analyzing downlink data, and making necessary adjustments to the AI systems. This dynamic approach ensures that the AI agents are not only effective but also align with the mission's strategic objectives. The proposal emphasizes the importance of explainability and transparency in AI systems, addressing technical, ethical, and legal challenges associated with AI integration in space operations.

In conclusion, the resubmission of the proposal reflects a comprehensive update that incorporates the latest technological advancements and stakeholder feedback, ensuring that the development of autonomous AI agents for spacecraft operations is both innovative and aligned with current industry standards.

6 Bibliography

In this section, we present a curated list of references that have been instrumental in shaping the research and development of autonomous AI agents for spacecraft operations. The selected works focus on recent advancements and practical applications in the field, avoiding speculative ideas and emphasizing well-motivated applicability to space-related challenges. This bibliography serves as a foundation for understanding the current landscape and future directions in integrating AI into spacecraft systems.

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